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Abstract

Rocks metamorphosed under high-pressure (HP) and ultra high-pressure (UHP) conditions in subduction zones come back to the surface relatively soon after their burial and at rates comparable to plate boundary velocities. In the Mediterranean realm, their occurrence in several belts related to a single subduction event shows that the burial-exhumation cycle is a recurrent transient process. Using the Calabria-Apennine and Aegean belts as examples, we show that the exhumation of HP rocks is associated in time and space with the subduction of small continental lithosphere blocks that triggers slab rollback, creating the necessary space for the exhumation of the buoyant continental crust that was deeply buried just before. The buoyancy force of the subducted crust increases until this crust detaches from the downgoing slab. It then exhumes at a rate that depends directly on the velocity of trench retreat to become part of the overriding plate. Heated from below by the asthenosphere that flows into the opening mantle wedge, the exhumed crust weakens and undergoes core complex-type extension, responsible for a second stage of exhumation at a lower rate. The full sequence of events that characterizes this model (crust-mantle delamination, slab rollback and trench retreat, HP rock exhumation, asthenosphere heating and core-complex formation) arises entirely from the initial condition imposed by the subduction of a small continental block. No specific condition is required regarding the rheology and erosion rate of HP rocks. The burial-exhumation cycle is transient and can recur every time a small continental block is subducted.

1. Introduction

Subduction offers a simple and widely accepted mechanism for the burial of crustal rocks down to mantle depths. However, with the discovery of ultra-high pressure (UHP) metamorphism in the Western Alps and the Norwegian Caledonides, we need to explain how rocks, buried at depths of 100 km or more, can make their way back to the surface soon after their burial and at rates comparable to plate boundary velocities (Ring et al., 1999; Chopin, 2003). This question also applies to high-pressure (HP) metamorphic rocks, such as blueschists and eclogites, commonly buried at shallower depths of 40-70 km (Platt 1993).

Exhumation of HP rocks corresponds to a vertical displacement of deeply buried material that must be accommodated by some type of overburden removal. If the trench does not move with respect to the upper plate, exhumation should occur by some type of channel flow (Cloos, 1982; Burov et al., 2001, Gerya et al., 2002), crust-mantle delamination (Chemenda et al., 1995) or slab break-off (Ernst et al., 1997). These mechanisms require either low viscosity of the exhuming material or extremely high erosion rates, and even if extension occurs, it cannot reach sufficiently high values to exhume rocks from more than some tens of km. If trenches move towards the upper plate, a hinterland-dipping normal fault can develop at the thrust system backstop, like in the Himalayas (Burg et al., 1984), that can accommodate a certain amount of exhumation (Beaumont et al., 2004). If the trenches move away from the upper plate- i.e. slab rollback (Dewey, 1981)- large-scale extension produces thinning and stretching of the upper plate and/or of the previously accreted units (Royden, 1993; Jolivet et al., 1994; Lister et al., 2001). In such domains, like the arcuate orogenic belts of the Mediterranean realm (Malinverno and Ryan, 1986; Royden 1993), there is much evidence of HP rocks being exhumed from depths of 70 km or more during continuous subduction (Jolivet et al., 1994; Lister et al., 2001; Jolivet et al., 2003). In contrast, postconvergence extension, as seen in the Basin and Range of the western USA, leads to exhumation of metamorphic rocks within core complexes (Crittenden et al., 1980), but the depth of exhumation remains limited to a maximum of 30-40 km.

The present paper analyzes the tectonic setting of HP units exhumation in two regions of the Mediterranean (Calabria-Apennines and the Aegean), that are fairly well constrained in terms of subduction kinematics, paleotectonic reconstruction and pressure-temperature history. From these two well documented examples we then propose a model of the exhumation of HP rocks associated in time and space with the subduction of small continental lithosphere blocks that trigger slab rollback, creating the necessary space for the exhumation of the buoyant continental crust that was previously deeply buried.

2. Subduction and exhumation of HP rocks in the Mediterranean realm

The Mediterranean orogenic belts formed during the slow convergence (about 1-2 cm/yr on average, Dewey et al., 1989; Rosenbaum et al., 2002a) between Africa and Eurasia, leading to the consumption of oceanic domains and the accretion of continental blocks. Subducted slabs are well imaged by seismic tomography, which reveals velocity anomalies spread over the entire Mediterranean domain (Wortel and Spakman, 2000; Piromallo and Morelli, 2003). Several HP metamorphic belts related to subduction crop out discontinuously along the whole Alpine belt from Gibraltar (Betic-Rif belt) to Anatolia (Lycian Taurus), passing through the Kabylides, Calabria, Northern Apennines, Alps and the Hellenides.

In the Central-Western Mediterranean subduction, developed mainly during the Tertiary. In Calabria (Fig. 1a), more than 1000 km of lithosphere has been consumed normal to the trench axis over the last 60 Ma (section AA’, figure 2l). This value is similar to that obtained from the tomographic cross-section (Fig. 2e), where a high-velocity anomaly reveals a rather steep slab flattening out at depth around the 660 km discontinuity. More than 800 km of subduction are due to the trench retreat that led to the opening of two back-arc basins (Faccenna et al., 1997; Guegen et al., 1997): firstly, the Liguro-Provencal basin (continental rifting: 30-21 Ma; seafloor spreading: 21-16 Ma), followed by the Tyrrhenian basin (continental rifting: 10-5 Ma; seafloor spreading: 5-1 Ma) (Figs. 1a and 2g-l). Therefore, Calabrian trench retreat occurred in two stages separated by a quiescent period from 15 to 10 Ma (Fig.1a). This intermittent behaviour has been interpreted as due either to deep deformation of the slab once it reached the 660 km discontinuity (Faccenna et al., 2001a), or to the entrance in the subduction zone of a small continental block (Bonardi et al., 2001; Rosenbaum et al., 2002b; Gattaceca et al., 2002), before the subduction of the present-day oceanic Ionian domain (Fig. 1a). In addition, the onset of backarc extension was concomitant with the entrance in subduction of another probably small (<200km) continental block as revealed by the age of HP continental derived units (Rossetti et al., 2001). The complex paleogeographic setting of the southern Tyrrhenian region gets simpler moving northward, where the onset of backarc extension is coeval with the entrance of Apulia-Adria continental margin, that keep slowly subducting until present-day (Jolivet et al., 1998; Faccenna et al., 2001b) (Fig. 1a).

Metamorphic, structural and radiometric dating reveals that the nappe stack exposed in Calabria formed during two distinct tectonic episodes (Rosetti et al., 2001; 2003). Syn-kinematic phengites from blueschist-facies rocks (P=0.6-1.2 GPa and T< 400°C) belonging to continental and oceanic units in Calabria yield Ar/Ar ages of 35 Ma and 15-20 Ma for the metamorphic peak and the retrogressive stage, respectively (Rossetti et al., 2001; 2003) (Figs. 1b and 2a-c). Top-to-west extensional deformation reworked, from the Lower Miocene to 15 Ma the previous nappe stack, accompanying exhumation of the HP units to upper crustal depth. The timing and style of exhumation described in Calabria is similar to the ones reconstructed for the HP units cropping out in the northern Apennines (Jolivet et al., 1998; 2003). We conclude that exhumation of HP continental blueschist rocks in Calabria and the northern Apennines occurred synchronously or just before the opening of the Liguro-Provencal basin (Fig. 1c).

In the eastern Mediterranean, subduction started earlier during the Mesozoic and consuming around 1200 km of lithosphere during the Tertiary (Figs1d and 2m-q) (Faccenna et al., 2003). Although seismic tomography images a single slab, surface geology records an imprint of the docking of two continental blocks and the associated consumption of three basins (Dercourt et al., 1993; Stampfli et al., 2002). To the north, the Vardar suture zone formed during the Late Cretaceous-Early Tertiary after the closure of the Tethyan ocean, and the arrival of the Pelagonian continental block. Further south, the Olympus-Cycladic blueschist belt is related to the closure of the Pindus oceanic basin in Mid-Eocene times and subsequent consumption of the Apulian block (Gavrovo, Tripolitsa and Ionian thrust units), below which the east Mediterranean oceanic basin is currently being subducted. The extensional history of the Aegean (Figs. 1d and 2f-l) starts in Mid-Eocene times in the Rhodope, to the north of the Vardar suture zone (Burchfiel et al., 2003; Brun et al., 2004, 2007; Kounov et al., 2004) and is exemplified by the large-scale Southern Rhodope Core Complex (SRcc) (Dinter and Royden, 1993; Sokoutis et al., 1993). Its early development (From 45 to 30 Ma) was coeval with the exhumation of blueschists in the Cyclades (Jolivet et al., 2003) and the subduction of the Pindos oceanic basin (about 42 Ma; Ferrière et al., 2004). During a second stage (From 24 to 10 Ma; see Fig.1d-f), extension continues in the SRcc but migrated southward leading to the development of the Cyclades Core Complex (Cycc) (Gautier and Brun, 1994), in which high-temperature deformation is overprinted onto the previous stage of blueschist exhumation. This is illustrated by the two-stage decompression history of HP rocks on Naxos and Tinos (Parra et al., 2002) (Fig. 1e). The development of the Cycc was coeval with the exhumation of blueschist rocks in

Crete and the Peloponese (Jolivet et al., 2004) as well as the onset of oceanic subduction of the eastern Mediterranean basin (Le Pichon et al., 2002) (Figs 1d-f and 2f-q). A third stage of extension started after the Messinian with the initiation of the North Anatolian fault and the westward displacement of Anatolia. The bulk amount of extension towards the NNE, parallel to the mean direction of finite stretching (Profile BB' in Fig. 2l), is estimated as about 580 km since the mid Eocene. The exhumation of the two HP belts of the Cyclades and Crete-Peloponese were synchronous with back-arc extension of core-complex type in the Southern Rhodope and the Cyclades, respectively (Fig. 2f). Moreover, the simultaneous development of the SRcc and exhumation of the Cycladic blueschists was at least partly synchronous with the subduction of the Pindos oceanic basin. Similarly, the simultaneous development of the Cycc and exhumation of the blueschists in Crete-Peloponese was likely correlated with the onset of subduction of the Ionian oceanic basin.

3. Exhumation driven by slab rollback

The exhumation of high-pressure rocks in the Mediterranean appears to be controlled by two linked requirements, subduction of a continental block and slab rollback, as portrayed in the conceptual model of Figure 3. During oceanic subduction (Fig. 3a), fragments of oceanic crust as well as sediments and crustal blocks scraped off the overriding plate can be brought to high-pressure metamorphic conditions. Following on from this, the subduction of continental crust is accommodated by shortening and thrusting, with the ductile crust acting as a basal décollement. Moreover, at the rear of the thrust wedge, crustal slivers are dragged down to HP or even UHP metamorphic conditions. If the compressional front reaches the ocean-continent boundary, the continental crust becomes entirely decoupled from the underlying mantle (Fig. 3c). Such a process would be related to the size of the block, which, in turn, scales with the ratio between the pull of the attached oceanic slab (which is negatively buoyant) and the positive buoyancy of the continent. Assuming average densities values (Cloos et al., 1993) for oceanic (3300 kg/m^3) and continental (3170 kg/m^3) lithosphere and for the upper mantle (3230 kg/m^3) and lithospheric thickness of about 100 km, the critical block size would be slightly (15%) larger than the length of the attached oceanic lithosphere. Considering the driving portion of the slab as confined in the upper mantle –i.e. 660 km- then the maximum length of the continental block that could be delaminated would be around 400 km, depending on slab dip. Because slab dip is a function of slab buoyancy (Garfunkel et al., 1986), the consumption of continental lithosphere (Fig. 3b) decreases the subduction rate, thus increasing the slab dip and favouring frontward migration of the trench (Martinod et al., 2005; Royden and Husson, 2006) (Fig3a to c). The resumption of oceanic crust subduction (Fig. 3d), would then increase the subduction rate, triggering trench retreat with two possible simultaneous consequences: i) fast exhumation of the deeply buried continental slivers and ii) back-arc extension. Exhumation of HP or UHP rocks results from the combined effects of an upward push by buoyancy forces and the space made available by trench retreat. The normal-sense shear zone, flat-lying on top of the exhumed HP rocks, results from the tectonic inversion of the suture zone and associated thrusts (Fig. 3d) (see Tso-Morari example in Lister et al., 2001)

Asthenosphere penetrates into the wedge that opens up between the exhuming crust and the slab (Figs. 3d to f), thus heating the crust, leading to subsequent partial melting and production of granites as well as thermal softening that allows the extension typical of core complexes. This is illustrated by the isobaric heating at a pressure of around 10 kbar that occurs during exhumation of the HP rocks of Tinos and Naxos (Parra et al 2002), that is also observed in exhumation history of the UHP rocks of the Alps (Rubatto and Herman, 2001) and Himalayas (De Sigoyer et al, 2002).

In exhumation driven by slab rollback, the exhumation rate is directly dependant on the velocity of trench retreat and the slab dip (Fig. 4). Our estimate of bulk extension (c.a. 580 km) accumulated in the Aegean since Mid-Eocene times (ca. 45 Ma) yields a mean velocity of trench retreat of around 12-13 mm/yr. However, the velocity of trench retreat could have been temporarily significantly higher than the calculated mean value and the present-day velocity of retreat of the Hellenic trench, which is given by GPS measurements as being of the order of 25-30 mm/y (McClusky et al., 2000) Since exhumation can be coeval with back-arc extension, the velocity of trench retreat can be partitioned between the exhumation of HP rocks and back-arc extension. The first step of decompression of the Tinos HP rocks (Parra et al, 2002) corresponds to a vertical displacement of 30 km in 7 Ma, giving a vertical rate of 4.3 mm/yr. The corresponding horizontal rates of displacement would be 4.9 and 6.1mm/yr for slab dips of 60° and 45°, respectively. Over the same period, the Southern Rhodope Core Complex accommodated 70 km of extension in 15 Ma, giving a mean value of 4.6 mm/yr. Summing these two components of extension yields trench retreat velocities of 9.5 and 10.7 mm/y, respectively. These estimates are relatively close to the mean Aegean extension rate of 12-13 mm/yr.

The high exhumation rates of up to 30 mm/yr that characterise the first phase of exhumation of UHP rocks to about 35-40 km depth have been recently compared with plate boundary velocities (Ring et al., 1999; Chopin, 2003; Rubatto and Hermann, 2001; Hacker et al., 2003). The model of slab-rollback-driven exhumation provides a straightforward explanation of this observation (Figs. 3 and 4).

The model presented here contains ingredients from previous models. The role of continental crustal block accretion and rollback in the build up and destruction of orogen was proposed for the Mediterranean belts (Jolivet et al., 1994; Lister et al., 2001; Rosenbaum and Lister, 2005) and for other regions, such as the Norwegian Caledonides (Hacker et al 2003) or the Himalaya (Lister et al., 2001). But our model differs from these previous ones as it considers not only a single and continuous subducting slab from which continental blocks are progressively delaminated and accreted to the overriding plate (Jolivet et al., 1994) but also the dip changes that result from density variations (Garfunkel et al., 1986). This scenario is supported by the high velocity anomalies distribution imaged by seismic tomography in the analyzed regions (Wortel and Spakman, 2000; Piromallo and Morelli, 2003; Faccenna et al., 2003). The crust-mantle delamination and variations in slab dip due to density changes are indeed central to our model as these factors are not only able to trigger rollback (Martinod et al., 2005; Royden and Husson, 2006) but also have profound consequences for the thermal evolution of the orogen, because newly exhumed crustal HP slivers float directly on top of the incoming asthenosphere. Such a thermal overprint is not only observed in the Aegean but also in other regions like the Northern Apennines (Jolivet et al., 1998), Betics (Platt et al., 1988), Alps (Rubatto and Herman, 2001) and Himalayas (De Sigoyer et al., 2002). The abundance of upper crustal slivers stacked in the Mediterranean belts manifests the efficiency of delamination of the upper crustal units from the lower ones. Indeed, the delamination process and buoyancy effect have already been taken into account in previous studies (Chemenda et al., 1995; Ernst et al., 1997). However, because these models do not involve divergence of the external boundaries of the deforming system, additional conditions must be added, such as high erosion rates or low ductility of HP rocks.

Conclusion

We have shown that the exhumation of HP rocks in the Calabria-Apennine and Aegean belts is associated in time and space with the subduction of small continental lithosphere blocks that trigger slab rollback. This creats the necessary space for the exhumation of the buoyant continental crust that was deeply buried just before. From the geological and geophysical evidence available for these two well-documented examples and in comparison with other examples, we proposed a model of HP-UHP rocks exhumation driven by slab rollback. The sequence of events that characterizes this model –i.e. crust-mantle delamination, slab rollback and trench retreat, HP rock exhumation, heating by the asthenosphere and core-complex extension- arises entirely from the initial condition imposed by the subduction of a small continental block. No specific condition is required regarding the rheology and erosion rate of HP rocks, but to ensure delamination of crustal sliver, its positive buoyancy force must overcome thhe shear strength of the lower crust. Finally, the burial-exhumation cycle in this model is transient and can recur every time a small continental block is subducted.

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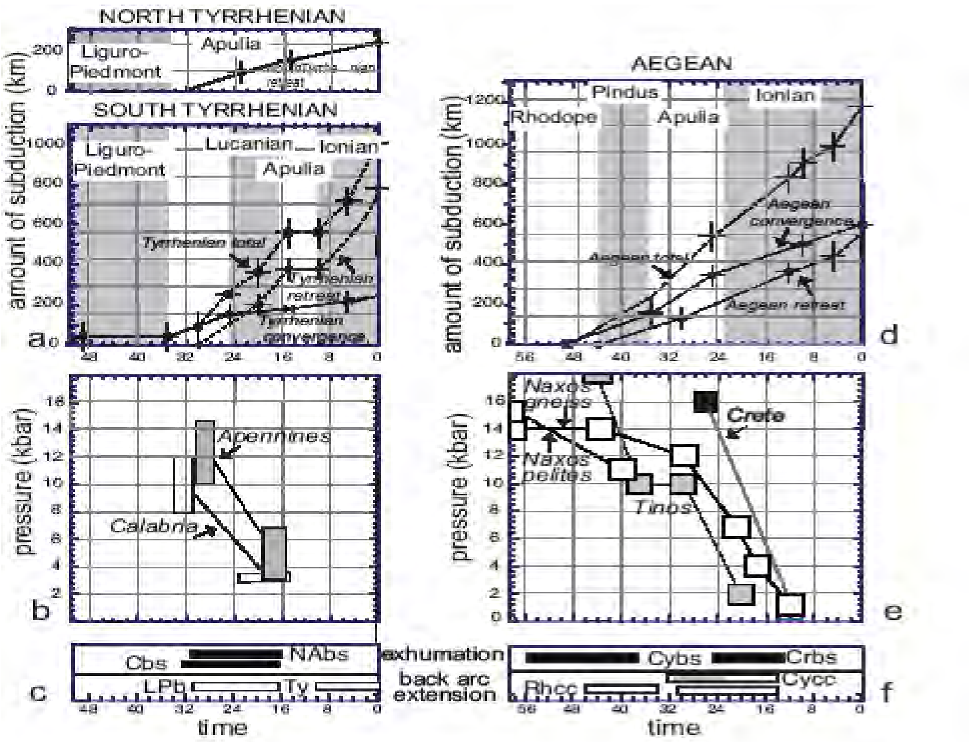

FIGURE1

Figure 1. Tectonic constraints used to reconstruct the subduction-exhumation history in the Central and Eastern Mediterranean. Upper panels (a, d) show the amount of net subduction on the Apennine-Calabrian and Hellenic trench. The rate of subduction has been estimated by summing the amount of convergence between Africa and Eurasia and the amount of trench retreat. The former is calculated from the convergence component normal to the trench axis using Dewey et al.'s (1989) rotation pole for Africa with respect to Eurasia and assuming that the Apulia continental block followed the same path. For the Calabria-Apennine belt, the amount of trench retreat is estimated by subtracting the oceanic crust from the back-arc basin and by restoring the thinned continental crust to the thickness of its shoulders, using an area-balancing technique (Faccenna et al., 1997). For the Aegean, where extension is dominantly accommodated by core complexes and lower crustal flow, the amount of extension is assumed equal to

the surface width of the exhumed metamorphic rocks (i.e. Cyclades and Rhodope in the Aegean domain). An independent check is provided by block rotation, using paleomagnetic data and the correlation of geological markers (Brun and Sokoutis, 2007). Blue and yellow indicate the subduction of deep basin (oceanic) and continental block, respectively (modified from Dercourt et al., 1993). Panels b and e show pressure-age paths of some selected metamorphic cores cropping out in Calabria-northern Apennines (b) and Cyclades-Crete (Gautier and Brun, 1994; Parra et al., 2002; Jolivet et al., 2003) (e). Panel c and f show the relationships between exhumation of HP units and extension in the hinterland area for the Calabria-Apennine trench and Hellenic trench, respectively (Nabs: Northern Apennines blueschist; Cbs: Calabrian blueschist; LPb: Liguro-Provencal basin; Ty: Tyrrhenian basin; Cybs: Cyclades Blueschist; Crbs: Crete Blueschist; SRcc: Southern Rhodope core complex; Cycc: Cyclades core complexes).

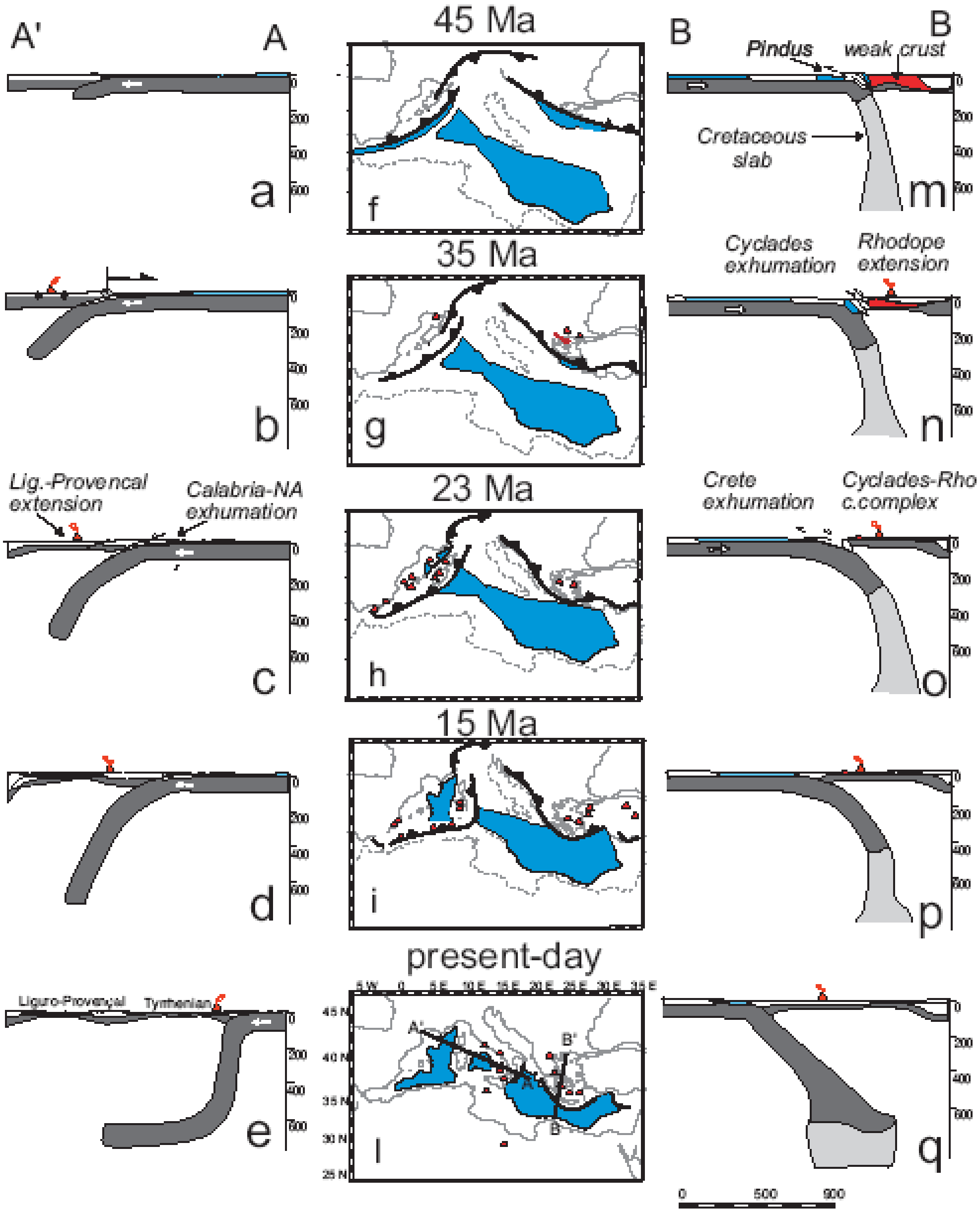

Figure 2. Tectonic reconstruction of subduction and back-arc extension in the Mediterranean. Five crucial time lines are shown (a-e): 43, 35, 23, 15 Myr ago and present day. Central panels (f-i): schematic tectonic reconstructions of the Central Mediterranean with respect to a fixed Europe reference (modified from Dercourt et al., 1993; displacement of Africa from Dewey et al., 1989; the path for Apulia is assumed consistent with Africa); only major tectonic elements are schematically shown, including the location of deep oceanic basins (blue) the Alpine, Calabria-Apennine and Hellenic trenches and the main volcanic fields (red triangles). Right and left panels show the corresponding five stages of subduction along the reference section AA' Calabria-Gulf of Lyons (right a-e) and BB' Cyrenaica (Lybia)-Rhodope (left, m-q), respectively. The present-day shape of the slab is derived from the tomographic images of Wortel and Spakman (2000) and Piromallo and Morelli (2003).

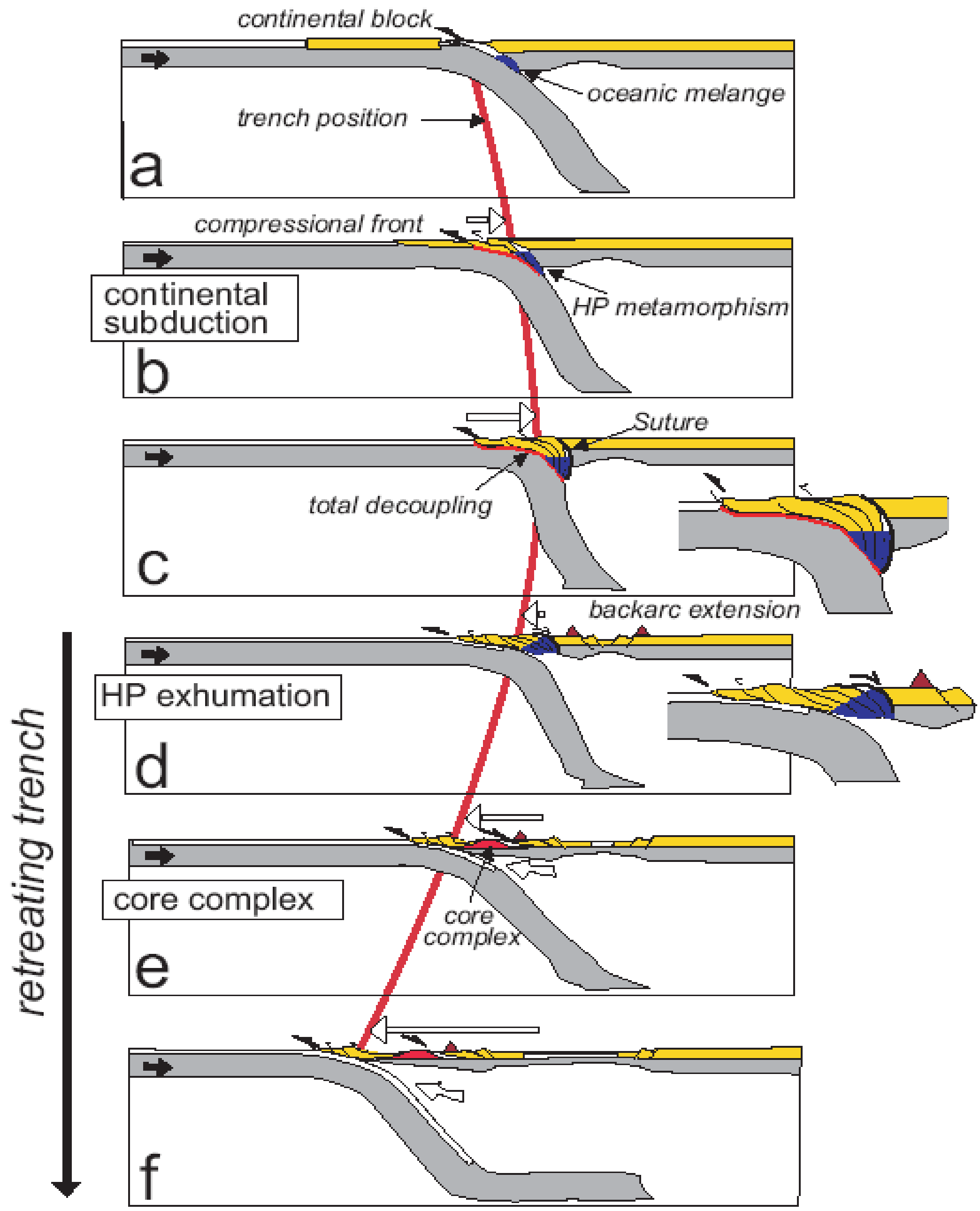

Figure 3. Model of exhumation driven by slab rollback: continental subduction stage (a to c), exhumation of high-pressure (HP) rocks (d) and exhumation of high-temperature (HT) rocks in core complex (e). The red line indicates trench retreat, while the white arrows indicate the trench advance (a to c) and retreat (d to f). Slab dip increases during subduction of the continental block (a to c), and then decreases during oceanic subduction (d to f). See text for detailed discussion.

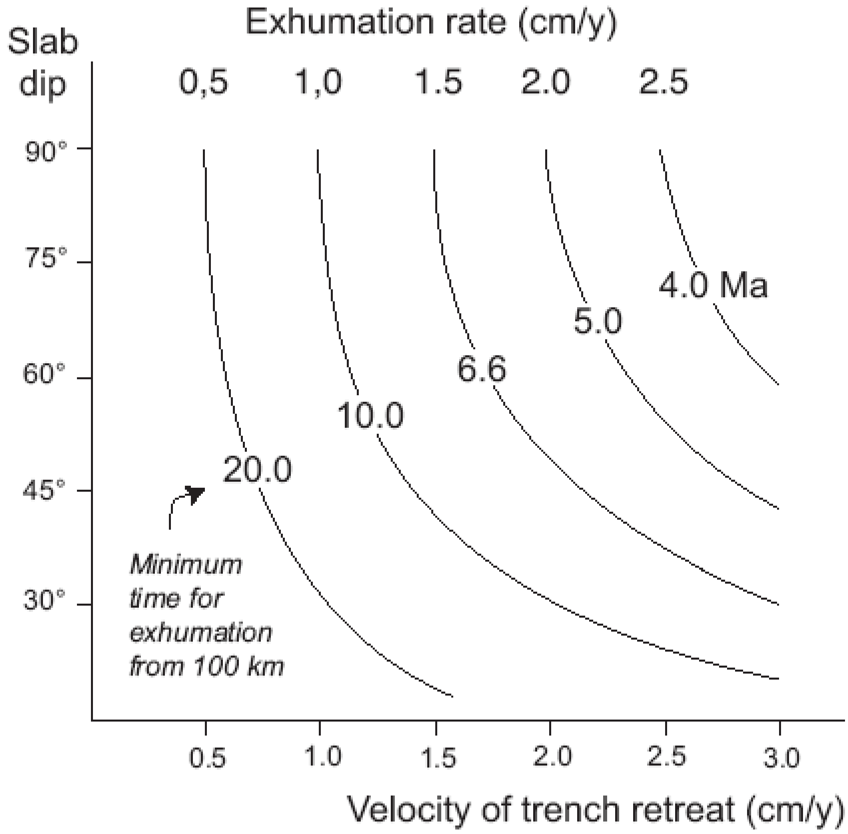

Figure 4. Diagram showing the exhumation rate as a function of velocity of trench retreat and slab dip in the model of slab-rollback-driven exhumation.